Nano-Proprietary, Inc. (formerly SI Diamond)

# Using Field Emission Display Technology to Demonstrate HDTV

*By the mid-1990s, several flat panel display (FPD) technologies offered varying degrees of color luminance, screen size, contrast, viewing angle, minimal after-images, and voltage consumption. However, no single technology provided all these features to support high-definition TV (HDTV). To fill this gap, SI Diamond, an FPD developer, and Supertex, a manufacturer of high-voltage integrated chips, formed a joint venture to improve a type of FPD, the field emission display (FED). Significant progress might enable the United States to compete successfully against Japan, the market leader in FPDs. The goal of the joint venture was to combine the high-brightness image quality of the bulky cathode ray tube (CRT) and the thinner display format of the liquid crystal display (LCD) in a prototype display. Technical risks centered on the difficulty in generating a high density of identical, microscopic emission sites that produced uniform emission and high-definition image appearance. The joint venture applied for and won an Advanced Technology Program (ATP) award in 1994, and their project started in 1995.*

*SI Diamond, which changed its name to Nano-Proprietary, Inc. in 2003, learned critical lessons during the ATP-funded project, which spurred further carbon nanotube (CNT) and FED development. The project produced 9 patents and led to 1 technical award and numerous publications and presentations. The company has developed a prototype CNT FED TV compatible with an 80-inch-diagonal HDTV and two CNT-based FED products: a carbon cathode for X-ray tubes and a controller module for electronic billboards. Two more CNT-based products are expected by 2009: a backlight for an LCD and an ultraviolet light source for air cleaners.*

**COMPOSITE PERFORMANCE SCORE**
(based on a four star rating)
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**Research and data for Status Report 94-01-0282 were collected during August – September 2005.**

## Joint Venture Seeks to Improve Flat Panel Display Technology

Flat panel displays (FPDs) present visual information in devices such as computer monitors, cell phones, and home entertainment systems. The Japanese dominated FPD technology in the mid-1990s, when several types of FPDs were available. The high-resolution active matrix liquid crystal display that uses amorphous silicon transistors at each pixel element was the first technology introduced, but it suffered from viewing-angle problems, low light emission, and high cost. The field emission display (FED) offered the promise of improved color luminance and contrast and limited after-images. While one-inch displays could be made from silicon FEDs, this approach was not satisfactory in larger screen sizes. Nor could the FED be used in high-definition TV (HDTV), which anticipated a large and growing market.

To address these shortcomings, in 1993, SI Diamond, an FPD developer, acquired Plasmatron Coatings, a developer and installer of industrial coating systems, in anticipation of adding coating technology to its amorphic diamond technology. This acquisition helped SI Diamond to develop a five-inch prototype display demonstration unit. Based on the successful prototype, the company felt confident it could perfect the technology for larger 10-inch screens. The company formed a joint venture with Supertex, an integrated

ASIC chip manufacturer. ASIC chips, or application-specific integrated circuits, are specially designed chips that provide unique functions. They can integrate several functions or logic control blocks into one single chip, lowering manufacturing cost and simplifying circuit board design. The joint venture proposed to perfect SI Diamond's amorphic diamond film technology as an electron emitter for FEDs.

*The high-resolution active matrix liquid crystal display suffered from viewing-angle problems, low light emission, and high cost.*

With FED technology, the joint venture hoped to combine the best characteristics of two existing technologies: the high-brightness image quality of the bulky cathode ray tube (CRT) with the thin, picture-frame footprint of the liquid crystal display (LCD). CRTs rely on long glass vacuum tubes. Three electron guns (red, green, and blue) send electron beams to the front of the tube and combine to form millions of colors. The front of the tube has a phosphor coating, which lights up from electron beam bombardment. Larger screens required longer tubes, making CRT displays bulky and heavy. LCDs were flat and lightweight, but their color image quality was poorer, particularly in environments with high ambient light, like outdoors.

The joint venture researchers proposed to develop digital FED technology, which consists of an array of tiny electron emitters arranged in many rows and columns. Each pixel element acts like a small CRT, causing the phosphor screen to light up when the electron strikes the phosphor. The team identified four critical components of their proposed technology: pixelated arrays of a million field emitter devices that could produce a uniform, bright emission of electrons; a phosphor screen; high-voltage integrated chip drivers to control the screen display (normal chips operate at low voltage); and a suitable vacuum envelope and seal to house the electron emitters and phosphors, because electron emitters cannot operate in air. This process would be successful when the integrated circuit chip driver of a prototype FED applied power to the amorphic diamond-coated cathode array to cause electron emission. The electrons emitted from the diamond film would strike the phosphor coating on the anodes and would cause it to light up and display color images.

To accomplish their goals, in 1994 the joint venture applied for and received a two-year award from ATP to improve the amorphic diamond technology. The project started in 1995 and eventually ran for five years after the joint venture received several no-cost extensions. The companies hoped to improve the features of the FED so that they could effectively compete against foreign manufacturers. Japanese manufacturers held 95 percent of the global competing LCD-based FPD market, which was projected to reach $15 billion by 2000. FED project objectives included developing the technologies to create a working diamond FED prototype with its own integrated chip driver circuitry to present a viable alternative to LCD-based FPDs.

## Joint Venture Stimulates Collaboration

The joint venture used several subcontractors and collaborators to perform complex tasks necessary for FED development, including the following:

- Diamond Tech One, a subsidiary of SI Diamond, provided equipment and facilities for conducting the research.
- SI Diamond designed equipment and a chemical vapor deposition (CVD) reaction (engine) to produce the thin-film field emitters.
- Full Spectrum provided low-cost vacuum sealing.
- Thomas Electronics provided FED components, such as a phosphor-coated anode.
- The David Sarnoff Research Center developed low-voltage, high-efficiency powder phosphors useful for color amorphic diamond FEDs (DFEDs).
- Plasmatron Coatings (subsidiary of SI Diamond) designed equipment and developed the CVD reaction engine to produce the carbon film.
- Supertex developed the specialized high-voltage ASIC chips needed to drive the FED displays. Conventional semiconductor chips operate at low voltages, not the high voltages needed for these FED displays.

## Research Encounters Technical Difficulties

In addition to the FED, the project researchers explored developing two other types of FPDs, the picture element tube (PET) and the hybrid CRT/FED panel (HyFED). Among the many tasks performed during the project, the following six are worth noting:

- **Task 1**: **Electron emission density**. Researchers intended to improve the electron emission from the cathodes coated with the amorphic diamond film to a density of greater than 1 million per centimeter squared (1 M/cm$^2$) sites as evidenced on the display screen.
  **Results**: SI Diamond performed this task but abandoned their efforts in early 1997. Researchers discovered there was a problem with the laser ablation process to produce amorphic diamond thin films; the laser threw chunks of graphite onto the glass substrate, resulting in an uneven coating. Emission site densities of 50K/cm$^2$ were achieved, far short of the 1 million goal and too low for high-resolution images intended for HDTV. Consequently, the integrated chip driver development by Supertex to run the FED was delayed, because the chip design could not be started until the deposition process was functional. This problem resulted in the first no-cost extension to the program. This method was ultimately abandoned in favor of thin-film CVD in which gaseous methane is converted to solid diamond thin films on a glass substrate.

  SI Diamond discovered that CVD nano-diamond films exhibited field emission similar to its proprietary amorphic diamond and was superior because it did not have the graphite contamination problem. This process used CVD to lay down a film on the inside of the glass screen. Even with this superior process, however, the developers were not able to achieve uniform, high-density electron emission sufficient for large-area FPD applications for two reasons. First, it was too difficult to make a resistive layer on top of the CVD layer that would not break down when high-voltage energy was applied (a resistive layer prevents unwanted electro-chemical reactions during device operation). Second, the researchers were unable to achieve electronic emissions greater than 50 K/cm$^2$ on the display screen.

- **Task 2**: **Display phosphor testing**. Researchers worked on developing low-voltage, high-efficiency powder phosphors useful for color amorphic DFEDs. The David Sarnoff Research Center performed this work.
  **Results**: Researchers tested color phosphors. SI Diamond developed proprietary methods that decreased the voltages necessary to make use of the color phosphors. These proprietary methods resulted in two patents.

- **Task 3**: **Phosphor anode deposition**. Researchers selected, evaluated, and developed a process to deposit low-voltage, high-efficiency phosphors on large-area glass anode plates.
  **Results**: The David Sarnoff Research Center evaluated two phosphor deposition processes that contributed to the phosphor display anodes developed in this project. As a prototype demonstration of the technology, research focused on developing PET displays, a type of FED used in automated, very-large-area, outdoor electronic billboards (to display scrolling text). Supertex developed a driver chip to control PET display rows. While this was never commercialized because of the lack of progress on satisfactory amorphic diamond field cathodes, Supertex may yet find other markets for these specialized chips, such as in large-area TVs where light-emitting diode (LED) technology cannot compete.

- **Task 4**: **Vacuum sealing**. SI Diamond developed processes for large-area vacuum sealing of the carbon field-emission cathodes and the phosphor anodes, for both diode and triode display configurations. (A diode display is a two-part electrical device that lets electrons pass through a vacuum from the cathode to the anode. A triode display is a three-part electrical device, including anode, cathode and gate electrode.) The goal was to develop a low-cost sealing technology for DFEDs. SI Diamond worked on this task along with Full Spectrum, a small consulting business specializing in pneumatics.
  **Results**: This task was successfully completed by sealing and testing one-inch and five-inch DFEDs for a vacuum seal with no leaks.

- **Task 5**: **Quick vacuum creation**. SI Diamond developed processes for quickly evacuating air from within large DFEDs.
  **Results**: The evacuation was performed on the anode-cathode assembly. In this task, switching from DFEDs to PETs solved many technical difficulties. SI Diamond teamed with two Japanese companies, Sangyo and ISE Electronics Corporation, which gave advice on this task. This work led to later collaborations with Japanese manufacturers.

- **Task 6**: **Video graphics array**. SI Diamond intended to fabricate a 10-inch video graphics array display, with 640 by 480 pixels, in an FED prototype. Called a "HyFED," the device was a hybrid of a CRT and a FED. This task aimed to combine the results from the previous tasks to fabricate the 10-inch FED prototype. The goal for this task changed after its start; researchers increased the size of the prototype they were fabricating to a wall-size display. Supertex assisted in developing the chip driver.
  **Results**: SI Diamond demonstrated a color HyFED device in a vacuum chamber. Four Japanese companies and one European company assisted in this task by providing expertise. Expertise was also contributed by the Moscow State University in Russia, which provided a facility to test aspects of the CVD cathode.

***The joint venture hoped to combine the best characteristics of two existing technologies: the high-brightness image quality of the bulky cathode ray tube (CRT) with the thin, picture-frame footprint of the liquid crystal display (LCD).***

Oriented carbon nanotubes (CNTs) function as cathodes to emit electrons. SI Diamond researchers successfully applied a CNT film on a 15-inch-diameter screen with excellent electron-emission properties. CNTs are tiny, hollow cylinders 10,000 times smaller than a human hair. Their small size enabled increased emission-site density, which was superior to the CVD process. CNT electron emission enables a brighter, more efficient display. On the strength of this development, SI Diamond later focused on depositing CNT film on display screen glass in its continued research, while at the same time pursuing work on the HyFED concept.

## SI Diamond Continues Post-ATP Product Research and Alliances

Toward the end of the ATP-funded project in 2000, SI Diamond began its research in CNT. The company solicited additional funding from other sources to continue the research in the post-project period, including a Small Business Innovation Research (SBIR) award from the National Aeronautics and Space Administration to continue cathode research.

SI Diamond learned critical lessons from the ATP-funded project, which positioned them for later success. SI Diamond signed its first significant license agreement in 1999 with Canon, Inc. in exchange for a one-time, up-front payment of approximately $5.6 million. By July 2001, SI Diamond had developed a CVD-based carbon cathode as an electron source for Futaba, a manufacturer of flat panel displays and vacuum fluorescent displays. It also developed CNT-based electron sources for X-ray tube applications working with Oxford Instruments X-ray Technology group located near San Jose, CA. The CNT-based "cold" cathode suits small, portable applications, such as X-ray fluoroscopy to identify metals in an alloy or lead in paint. Because FED cathodes are higher brightness electron emitters than incandescent sources that 'boil off' electrons, the X-ray tube does not need a large filament power source. The cold cathode can emit electrons at room temperature and, therefore, provide an "instant on" mode of operation. The tube controller is smaller, lighter, and more rugged. Very small tubes could be inserted in human arteries, the colon, or the esophagus for radiation treatment. They can also be used to find cracks in pipe welds and airplane wings. SI Diamond has earned revenues of $1.4 million from both the X-ray tube and the electronic billboard module.

Since 2002, the company has made progress in developing CNT applications. The company has signed licensing agreements and has pursued alliances with several global companies. For example, in October

2004, SI Diamond, under its new name, Nano-Proprietary Inc., signed a letter of intent to develop new products with Shimane Masuda Electronics to use CNT sources backed by the large patent portfolio held by Applied Nanotech, a subsidiary of Nano-Proprietary. Dr. Richard Fink, Vice President of Engineering at Applied Nanotech, said that as a result of ATP assistance the company achieved a working CNT technology two to four years sooner. According to Dr. Fink, the joint venture between SI Diamond and Supertex would not have proceeded without ATP assistance. Furthermore, the project encouraged SI Diamond to become more collaborative in its research efforts and to seek more cooperative research agreements with global companies.

## Proof of Concept Leads to Industry Award

In September 2005, Nano-Proprietary announced a completed proof of concept for a high-resolution, full-color, 25-inch-diagonal CNT TV. The image and its characteristics are similar to the CRT, because like the original FED technology concept, CNT FED TVs are a flat and thin extension of the CRT technology. The proof of concept operates at a voltage that is compatible with low-cost complementary metal-oxide semiconductor (CMOS) drivers. The distance between subpixels, about .5 mm, makes the printing techniques compatible with 60-inch-diagonal advanced TV format and 80-inch-diagonal HDTV. "This proof of concept is a critical achievement in that the processes…used in creating the display will allow manufacturers to dramatically reduce the capital investment needed to produce CNT TVs," said Dr. Zvi Yaniv, Chief Executive Officer of Applied Nanotech. They are now capable of creating "close to 10 million sites per $cm^2$, depending on the extraction field," he said. "We try to keep the voltage CMOS-compatible, and today we can do around 250,000 sites per $cm^2$ at around 10 V/micrometer or less." Six Japanese FPD component manufacturers also contributed to the development of the 25-inch prototype. Nano-Proprietary and Dr. Yaniv received a 2005 Nanotech Briefs' Nano 50 Award in November 2005 for technology and innovation. The award recognized the company for its work in CNT FEDs.

The company plans two more CNT-based products within four years: ultraviolet air cleaners and an LCD backlight.

***Dr. Richard Fink, Vice President of Engineering at Applied Nanotech, said that as a result of ATP assistance the company achieved a working carbon nanotube (CNT) technology two to four years sooner.***

## Conclusion

SI Diamond and Supertex formed a joint venture in 1994 to perfect SI Diamond's amorphic diamond film as an electron emitter for field emission displays (FEDs). Japanese manufacturers dominated the flat panel display (FPD) industry, and SI Diamond intended to provide an opening for U.S. manufacturers. The joint venture planned to combine the best qualities of the liquid crystal display (LCD) of light weight and flat size and the first widely used display technology, the cathode ray tube (CRT), which had excellent color and luminance. The FED technology required the development of a thin film field emission array cathode, a reliable long-life screen phosphor anode, a vacuum tight envelope with good sealing, and an integrated high-voltage chip driver to control the display. After working on two methods for applying diamond emitters to a surface, SI Diamond finally switched to a third carbon-based option of carbon nanotubes (CNTs), a technology added late into the project schedule. The company learned key lessons during the ATP-funded early development. Project researchers disseminated knowledge through 9 patents, 1 technical award, and numerous publications and presentations. SI Diamond developed two products from the platform technology that evolved after the project ended: a module for electronic billboards and carbon cold cathodes for X-ray tubes. SI Diamond, which changed its name to Nano-Proprietary, Inc. in 2003, demonstrated a prototype CNT-based flat-screen TV technology in 2005 and has formed several alliances with global FPD developers to continue its development of CNTs. Nano-Proprietary plans two more CNT-based products in two to four years: ultraviolet air cleaners and an LCD backlight.

# PROJECT HIGHLIGHTS
# Nano-Proprietary, Inc. (formerly SI Diamond)

**Project Title:** Using Field Emission Display Technology to Demonstrate HDTV (Diamond Diode Field Emission Display Process Technology Development)

**Project:** To develop and demonstrate the critical processing technology needed to develop a flat panel display (FPD) based on a new concept using high-brightness, diamond-coated field-emission cathodes.

**Duration:** 6/1/1995 - 5/31/2000
**ATP Number:** 94-01-0282

**Funding (in thousands):**

| | | |
|---|---|---|
| ATP Final Cost | $3,465 | 45.8% |
| Participant Final Cost | 4,094 | 54.2% |
| Total | $7,559 | |

**Accomplishments:** With ATP funding, Nano-Proprietary, Inc. (formerly SI Diamond) and joint venture partner, Supertex, learned key principles concerning emission display technology. Although the original materials focus of diamond-coated cathodes failed, Nano-Proprietary made important developmental strides:

- The company used chemical vapor deposition (CVD) to deposit thin-film diamond field emitters and made prototype five-inch field emission displays (FEDs). While an important proof of concept was demonstrated, these displays exhibited low emissivity (< 50,000 electron emissions per centimeter squared [50 K/cm$^2$]).
- Researchers developed a proprietary method that decreased the voltages necessary to make use of the color phosphors.
- Supertex developed high-voltage chips to drive the diamond-based field emitters.
- SI Diamond developed processes for large-area diode vacuum sealing, which is needed for electron emissions.
- The company demonstrated a 10-inch color video graphics array display in a vacuum chamber, with 640 by 480 pixels, in an FED prototype. Called a "HyFED," the device was a hybrid of a cathode ray tube (CRT) and an FED. Supertex assisted in developing the chip driver.
- Work started on a third carbon materials FED option of carbon nanotubes (CNTs), which has proved to be very successful.

Nano-Proprietary and Dr. Zvi Yaniv, CEO of Applied Nanotech, Inc. were named winners in the 2005 Nanotech Briefs' Nano 50 Awards for technology and innovation held November 2005 in Boston, MA. Applied Nanotech is a wholly owned subsidiary of Nano-Proprietary. The award recognized the company for its work in CNT FEDs.

Nano-Proprietary received the following 9 patents for technologies related to the ATP-funded project:

- "Composition and method for preparing phosphor films exhibiting decreased coulombic aging"
  (No. 5,853,554: filed March 27, 1996, granted December 29, 1998)
- "Field emission device with edge emitter and method for making"
  (No. 5,818,166: filed July 3, 1996, granted October 6, 1998)
- "Backlights for color liquid crystal displays"
  (No. 5,926,239: filed November 22, 1996, granted July 20, 1999)
- "Method of forming a cathode assembly comprising a diamond layer"
  (No. 5,947,783: filed August 26, 1997, granted September 7, 1999)
- "Display"
  (No. 5,973,452: filed August 26, 1997, granted October 26, 1999)
- "Composition and method for preparing phosphor films exhibiting decreased coulombic aging"
  (No. 5,906,721: filed October 27, 1997, granted May 25, 1999)
- "Heating element for use in a hot filament chemical vapor deposition chamber"
  (No. 6,432,206: filed February 23, 2000, granted August 13, 2002)
- "Substrate support for use in a hot filament chemical vapor deposition chamber"
  (No. 6,582,780: filed February 23, 2000, granted June 24, 2003)
- "Gas dispersion apparatus for use in a hot filament chemical vapor deposition chamber"
  (No. 6,692,574, filed February 23, 2000, granted February 17, 2004)

# PROJECT HIGHLIGHTS
# Nano-Proprietary, Inc. (formerly SI Diamond)

**Commercialization Status:** Nano-Proprietary learned key concepts from the ATP-funded FED project concerning higher emission site density. This led to continued CNT technology development. As of 2005, the company had two CNT products in the market: carbon cathodes for X-ray tubes and controller modules for electronic billboards. Nano-Proprietary anticipates two additional CNT-based products within four years: liquid crystal display (LCD) backlights and ultraviolet air cleaners. In September 2005, Applied Nanotech, a subsidiary of Nano-Proprietary, announced a demonstration 25-inch flat screen TV. Results showed a significant improvement over LCD and plasma TV (another type of FPD).

**Outlook:** The outlook for Nano-Proprietary's CNT technology is good but clouded. The original ATP-funded diamond-coated cathode technology failed, but the company learned critical lessons, which enabled it to develop CNT technology. Global competition is fierce. The company seeks commercial partners and continues to develop new CNT-based technologies beyond TVs, X-ray tubes, and electronic billboards. Industry sales of CNT electronics are expected to reach $3.6 billion by 2009.

**Composite Performance Score: * * * ***

**Number of Employees:** 10 employees at project start, 30 as of September 2005


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**Subcontractors:**

- David Sarnoff Research Center
  Princeton, NJ
- Diamond Tech One (subsidiary of SI Diamond)
  Austin, TX
- Full Spectrum
  Colorado Springs, CO
- Plasmatron Coatings (subsidiary of SI Diamond)
  Moorestown, NJ
- Thomas Electronics
  Wayne, NJ

The joint venture partners shared their research extensively through the following publications and presentations.

**Publications:**


- Xie, Jamison. "FED Modeling." *Proceedings of IVMC '95*, Portland Oregon, July 31-August 4, 1995.
- "Carbon Based Cold Cathodes." *Proceedings of Diamond Films '95*, Barcelona, Spain, September 10-15, 1995.
- "DFED Update." *Proceedings of the AVS National Symposium*, Minneapolis, MN, October 16-19, 1995.
- "Considerations in Selecting Phosphors for Low Voltage FED Applications." *Proceedings of SID Conference*, Hamamatsu, Japan, October 16-18, 1995.
- "Phosphors for Low Voltage Field Emission Devices." *Proceedings of the Conference of Science and Technology of Display Phosphors*, San Diego, CA, November 14-16, 1995.
- "Diamond and Diamond-Like Materials for Use as Cathodes for Field Emission FPDs." *Proceedings of the MRS Fall Meeting*, Boston, MA, November 27-December 1, 1995.
- "Microstructures of Amorphic Diamond (TM) Films Deposited by Laser-Ablation." *Proceedings of the MRS Fall Meeting*, Boston, MA, November 27-December 1, 1995.
- "Highly Efficient Field Emission Backlights for Liquid Crystal Displays." *Proceedings of the International Display Workshop (IDW) '96 Conference*, Kobe, Japan, November 27-29, 1996.

# PROJECT HIGHLIGHTS
# Nano-Proprietary, Inc. (formerly SI Diamond)

- "Performance and Applications of Diamond Cold Cathodes.” (white paper) *SID '97 Show in Boston*, April 1997.
- "Electron Emission from Patterned Diamond Flat Cathodes." *Proceedings of the IVMC '97 Conference*, Kyongju, Korea, August 17-21, 1997.
- "The Status and Future of Diamond Thin Film FED." *Proceedings of the Nikkei Microdevices Conference*, Pacifico Yokohama, Japan, October 29, 1997.
- Fink, R.L., Zvi Yaniv, and Zi Li Tolt. “The Status and Future of Diamond Thin Film FED”, *Surface and Coatings Technology*. Vol. 108-109: pp. 570-576, 1998.
- Robinder, R. C., Z. Yaniv, R. L. Fink, Z. Li Tolt, and Lief Thuesen. "Application of Diamond Thin-Film Cathodes to the Hybrid Field Emission Display/CRT (HyFED)." *Proceedings of the Fifth International Display Workshops (IDW '99)*, Kobe, Japan, 1998.
- Tolt, Z. Li, R. L. Fink, and Zvi Yaniv. "Carbon Thin Film Cathode for Large Area Display." *Proceedings of the Fifth International Display Workshops (IDW '99)*, Kobe, Japan, 1998.
- Fink, R. L., Z. Yaniv, and Z. L. Tolt. “Lifetime and Stability of Diamond Field Emission Devices.” *2nd Int. Symposium on Diamond Electronic Devices*, Vol. 8, No. 6, pp. 435-440, 1998.
- Marrese, C. M., J. E. Polk, K. L. Jensen, A. D. Gallimore, C. Spindt, R. L. Fink, Z. L. Tolt, and W. D. Palmer. “Performance of Field Emission Cathodes in Xenon Electric Propulsion System.” Chapter 11 in *Micropropulsion for Small Spacecraft*, Michael M. Micci and Andrew D. Ketsdever, Editors, Paul Zachen, Editor-in-Chief. *Progress in Astronautics and Aeronautics*, Vol. 187, AIAA.
- "The Status and Future of Diamond Thin Film FED." *Proceedings of the Gorham Conference*, Tampa, FL, March 2-4, 1998.
- "Lifetime and Stability of Diamond Thin Film FED." 2nd International Symposium on Diamond Electronic Devices, Osaka, Japan, March 1998. Published in *Diamond Film*, Vol. 8, No. 6, pp. 435-440, 1998.
- "Emitting Carbon Thin Films and Their Characterizations." *Proceedings of the Meeting of the Materials Research Society*, San Francisco, CA, April 13-17, 1998.
- "The Status and Future of Diamond Thin Film FED." *Proceedings of the International Conference on Metallurgical Coatings and Thin Films*, San Diego, CA, May 1998.
- Robinder, R. C., Z. Yaniv, R. L. Fink, Z. Li Tolt, and Lief Thuesen. "The Hybrid Field Emission Display/CRT, a Novel Flat Panel Display." *Proceedings of the International Display Research Conference (Asia Display '98)*, Seoul, Korea, September 1998.
- Tolt, Z. L., R. L. Fink, L. H. Thuesen, L. Jacobs, and Zvi Yaniv. "Addressable Carbon Thin Film Cathode." *Proceedings of the International Display Research Conference (Asia Display '98)*, September 1998.
- Thuesen, L. H., Z. Li Tolt, Z. Yaniv, C. M. Marrese, S. Bandy, and C. Nishimoto. "Field Emission Carbon Thin Film and its Life Time and Stability." *Proceedings of IVMC 1999 Conference*, 1999.
- Marrese, C. M., J. E. Polk, K. L. Jensen, A. D. Gallimore, C. Spindt, R. L. Fink, Z. Li Tolt, and W. Devereux Palmer. "Lifetime and Performance of Field Emission Array Cathodes for Electric Propulsion Systems Environment." *Journal of Propulsion and Power*, *Special Issue on Microspacecraft Propulsion*, January 1999.
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## Presentations:

- Jamison, K., X. Chenggang, R. Fink, A. Ross, M. Kempel, N. Kumar, L. Ferdin and H. Schmidt. “Diamond and Diamond-Like Materials for Use as Cathodes in Field Emission Flat Panel Displays.” Diamond for Electronic Applications Symposium, Boston, MA, November 1995.
- Patterson, D. "Diamond and Diamond-Like Materials for Use as Cathodes for FEDs." MRS Fall Meeting, Boston, MA, December 11, 1995.

## PROJECT HIGHLIGHTS
## Nano-Proprietary, Inc. (formerly SI Diamond)

- Yaniv, Z., Z. Zvi, Z. Li, L. H. Tolt, R. C. Robinder, and R. L. Fink. "Prospect for Use of Diamond/Carbon Film for Field Emission Display Applications." Invited talk at the Fifth International Display Workshops (IDW '99), Kobe, Japan, December 1998.

- Yaniv, Z. "From the Concept of TV on the Wall to 'Wall TV' Utilizing Field Emission from Carbon Films." EuroDisplay '99, Berlin, Germany, September 6-9, 1999.

- Fink, R. L., Z. Li, L. H. Tolt, Z. Thuesen, and Z. Yaniv. "Carbon Cold Cathode Field Emission Picture Element Tubes for Large Area Displays." EuroDisplay '99, Berlin, Germany, September 6-9, 1999.

- Fink, Richard. "Status of Carbon Electron Emitting Films for Display and Microelectronic Applications." Pacific Northwest Chapter, Society for Information Display, Seattle, WA, April 25, 2002.